Mon. Not. R. Astron. Soc. **000**, 000–000 () Printed 1 February 2008 (MN LATEX style file v1.4)

Production of neutrons, neutrinos and gamma-rays by a very fast pulsar in the Galactic Center region

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Accepted Received ; in original form

ABSTRACT
We consider the possibility that the excess of cosmic rays near $\sim 10^{18}$ eV, reported by the AGASA and SUGAR groups from the direction of the Galactic Center, is caused by a young, very fast pulsar in the high density medium. The pulsar accelerates iron nuclei to energies $\sim 10^{20}$ eV, as postulated by the Galactic models for the origin of the highest energy cosmic rays. The iron nuclei, after about 1 yr since pulsar formation, leave the supernova envelope without energy losses and diffuse through the dense central region of the Galaxy. Some of them collide with the background matter creating neutrons (from desintegration of Fe), neutrinos and gamma-rays (in inelastic collisions). We suggest that neutrons produced at a specific time after the pulsar formation are responsible for the observed excess of cosmic rays at $\sim 10^{18}$ eV. From normalization of the calculated neutron flux to the one observed in the cosmic ray excess, we predict the neutrino and gamma-ray fluxes. It has been found that the 1 km^2 neutrino detector of the IceCube type should detect from a few up to several events per year from the Galactic Center, depending on the parameters of the considered model. Also future systems of Cherenkov telescopes (CANGAROO III, HESS, VERITAS) should be able to observe 1 - 10 TeV γ-rays from the Galactic Center if the pulsar was created inside a huge molecular cloud about $3 - 10 \times 10^3$ yrs ago.

Key words: Galaxy: center – Cosmic rays – pulsars: general – ISM: clouds – gamma-rays: theory – radiation mechanisms: non-thermal

1 INTRODUCTION

Recently the AGASA collaboration has reported the existence of an extended excess of cosmic rays (CRs) over a narrow energy range $10^{17.9} - 10^{18.3}$ eV from directions close to the Galactic Center (GC) and the Cygnus region with the significance of 4.5σ and 3.9σ, respectively (Hayashida et al. 1999). The GC excess was confirmed in the analysis of the SUGAR data (Bellido et al. 2001), in which case the observed signal in the energy range $10^{17.9} - 10^{18.5}$ eV is consistent with that from a point-like source of neutral particles, with an estimated flux of $(9 \pm 3) \times 10^{-14}$ m^{-2} s^{-1}, offset from the true location of the GC by about 7.5^{o}. Hayashida et al. (1999) suggested that such an anisotropy of CRs in a narrow energy range can be explained naturally by neutrons due to the fact that particles with such energies are able to reach the Earth before decaying from distance of the GC. Numerical simulations of charged particles (protons) propagation in reasonable models of the Galactic magnetic field give rise to the more extended source which may even be significantly shifted in the sky from the original direction towards the source (e.g. Clay 2000, Bednarek, Giller & Zielińska 2001). However, the results of charged hadrons propagation strongly depend on the details of the magnetic field model which is not well known at present.

The production of neutrons in discrete galactic sources was already discussed some time ago by Jones (1990), Sommers & Elbert (1990) and Bednarek (1992) in relation to reports of the excess of EeV particles from the direction of Cygnus X-3 (Cassiday et al. 1989, Teshima et al. 1990). It has recently been suggested that in the GC region neutrons might be produced in collisions of hadrons with matter (Takahashi & Nagataki 2001). Hadrons can be accelerated by a massive black hole associated with the Sgr A* (Levinson & Boldt 2000), or by the shock waves of supernovae which explode into their own stellar winds (Rhode, Enslin & Biermann 1998).

The Galactic Center region (inner $\sim$ 50 pc) is rich in many massive stellar clusters with a few to more than 100 OB stars (Morris & Serabyn 1996, Blum et al. 2001). These stars should soon explode as supernovae. In fact recent multiple supernova explosions in the GC region (10^3 supernovae in the past 10^5 years) are suggested by the observations of the diffuse hot plasma emitting X-rays (Yamauchi et al. 1990). For example one remnant of such a young supernova with the age of $\sim$ 80 years (G0.570-0.018)

has recently been reported by Senda et al. (2001). Since it is expected that pulsars are formed in explosions of such massive stars, we can expect that the GC region should contain some young pulsars, a number of them being $10^2 - 10^3$ yrs old. Motivated by these observational results we may assume that at least one of these young pulsars, formed in a supernova explosion of the type Ib/c, has parameters which allow the acceleration of iron nuclei to energies $\sim 10^{20}$ eV, as postulated by some models for the Galactic origin of the highest energy cosmic rays (Blasi, Epstein & Olinto 2000; De Goubeia Dal Pino & Lazarian 2000). We suggest that neutrons from desintegration of iron nuclei, which are accelerated by such energetic pulsar in the GC region, can be responsible for the observed excess of the cosmic rays with energies $\sim 10^{18}$ eV. Note that the iron nuclei with energies $\sim 10^{20}$ eV and neutrons with energies $\sim 2 \times 10^{18}$ eV have the same Lorentz factors. In order to test this hypothesis we predict the neutrino and γ-ray fluxes accompaning the process of neutron injection by iron nuclei.

2 A PULSAR INSIDE A MOLECULAR CLOUD

We investigate the scenario in which a very young pulsar is formed in a core collapse of the type Ib/c supernova immersed within a huge molecular cloud (or high density medium), characteristic of the GC region. Such supernovae are probably projenitors of neutron stars with extreme parameters (period, magnetic field surface), which allow them to accelerate iron nuclei to the highest energies observed in the CRs. In about a year after supernova explosion, the pulsar is surrounded by such a dense expanding envelope that hadrons, accelerated in the pulsar magnetosphere or the pulsar wind zone, are not injected into the surrounding. These hadrons lose energy on multiple inelastic collisions producing high energy neutrinos (Protheroe, Bednarek & Luo 1998, Bednarek 2001, Beall & Bednarek 2001). In later stages the particles can escape into the surrounding and diffuse in the magnetic field of the cloud, suffering collisions with the matter from time to time. In our further considerations we discuss, as an example, two media typical of the GC region in which the pulsar may be immersed. The first one is a huge molecular cloud with the radius $R_c = 10$ pc, the density $n_c = 10^3$ cm^{-3}, and the magnetic field $B_c = 10^{-4}$ G (the total mass $\sim 10^5 M_\odot$), and the second one is an extended high density region inside the GC with $R_c = 50$ pc, $n_c = 10^2$ cm^{-3}, and $B_c = 3 \times 10^{-5}$ G (the total mass $\sim 10^6 M_\odot$). The clouds with such parameters are typical of the GC region and of the Nuclear Bulge, which is a narrow layer of the interstellar matter in the central ~ 600 pc of the Galaxy with the height of ~ 50 pc.

2.1 Acceleration of nuclei by a pulsar

Following the recent works of Blasi, Epstein & Olinto (2000), Beall & Bednarek (2001), and Bednarek (2001) we assume that pulsars can accelerate iron nuclei in its wind zone (the mechanism called magnetic slingshot, Gunn & Ostriker 1969). The maximum energies which the nuclei can reach in this model, are determined by the magnetic field energy per particle in the pulsar wind zone and depend on the pulsar parameters as,

$$E_{\rm Fe} = \frac{B^2(r_{\rm LC})}{8\pi n_{\rm GJ}(r_{\rm LC})} \approx 1.8 \times 10^{11} B_{12} P_{\rm ms}^{-2} \ {\rm GeV}, \quad (1)$$

where $P = 10^{-3} P_{\rm ms}$ s is the pulsar period, $B = 10^{12} B_{12}$ G is the pulsar's surface magnetic field, $n_{\rm GJ} = B(r_{\rm LC})/(2ecP) \approx 3.3 \times 10^{11} B_{12} P_{\rm ms}^{-4}$ cm³ is Goldreich & Julian (1969) density, $r_{\rm LC} = cP/2\pi \approx 4.77 \times 10^6 P_{\rm ms}$ cm, and c is the velocity of light. According to the slingshot mechanism, the acceleration of nuclei occurs very fast so that they do not lose energy during this stage. During the first ~ 1 yr after explosion these nuclei interact with the radiation field and matter of the supernova envelope (Beall & Bednarek 2001). Only when the envelope becomes transparent, can the iron nuclei be injected into the surrounding of the parent pulsar's supernova. We obtain the spectrum of iron nuclei injected by the pulsar following the derivation by Beall & Bednarek (2001). Their calculation is based on the general prescription given by Blasi, Epstein & Olinto (2000) in which the number of nuclei accelerated to energies E scales as a part ξ of the Goldreich & Julian (1969) density at the light cylinder radius. Beall & Bednarek (2001) modify this approach by noting that the spectrum injected by the pulsar at a fixed time 't' should be non-monoenergetic due to the fact that the magnetic energy density, responsible for the acceleration of particles, changes along the pulsar's light cylinder height. As a result, a pulsar with specific parameters injects nuclei with the spectrum which can be below $E_{\rm Fe}$ described by (see details in Beall & Bednarek 2001),

$$\frac{dN}{dEdt} = \frac{2\pi c\xi r_{\rm LC}^2 n_{\rm GJ}(E_{\rm Fe}E^2)^{-1/3}}{3\left[(E_{\rm Fe}/E)^{2/3}-1\right]^{1/2}} \cong \frac{3\times 10^{30}\xi(B_{12}P_{\rm ms}^{-2}E^{-1})^{2/3}}{\left[(E_{\rm Fe}/E)^{2/3}-1\right]^{1/2}} \ \frac{\rm Fe}{\rm s\ GeV}. \quad (2)$$

We estimated that these nuclei can escape through the supernova envelope after ~ 1 yr after the supernova explosion for typical parameters of the supernova, i.e the mass of the envelope in the case of type Ib/c supernovae $M_{\rm env} = 3M_\odot$, and the expansion velocity of the envelope at the inner radius is $v_{\rm env} = 3 \times 10^8$ cm s^{-1} (Beall & Bednarek 2001). The iron nuclei diffuse in the magnetic field of the high density medium in the GC region, i.e. huge molecular clouds. Some of them interact producing neutrons, neutrinos, and γ-rays.

In order to obtain the equilibrium spectrum of iron nuclei inside the cloud, we have to integrate over the activity time of the pulsar since its parameters evolve in time due to the pulsar's energy losses. If we assume that the pulsar loses energy only on electromagnetic waves, then its period changes according to the formula $P_{\rm ms}^2(t_{\rm obs}) = 1.04 \times 10^{-9} t_{\rm obs} B_{12}^2 + P_{0,\rm ms}^2$, where $P_{0,\rm ms}$ $P_{\rm ms}(t_{\rm obs})$ are the initial and present periods of the pulsar. The equilibrium spectrum of iron nuclei at a specific observation time, $t_{\rm obs}$, is calculated from

$$\frac{dN}{dE} = \int_{t_0}^{t_{\rm obs}} \frac{dN}{dEdt} K e^{-c(t_{\rm obs}-t)/\lambda} dt, \quad (3)$$

where $t_0 = 1$ yr, K gives the part of nuclei produced at the time 't' which do not escape from the cloud due to the diffusion and are still present inside the cloud at the time $t_{\rm obs}$. λ is the mean free path for collision of the iron nuclei with the matter of the cloud. Note that for the parameters consid-

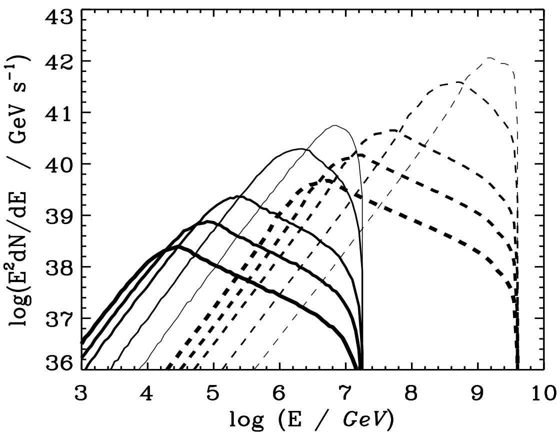

Figure 1. The differential spectra of neutrons (dashed curves) and γ-rays (full curves) produced in the interactions of iron nuclei with the matter of a molecular cloud with the radius $R_{\rm c} = 10$ pc, density $n_{\rm c} = 10^3$ cm^{-3}, and the magnetic field $B_{\rm c} = 10^{-4}$ G, at the time after the pulsar formation: t = 10, 10^2, 10^3, 3×10^3, and 10^4 yr (from the thinnest to the thickest curve). The initial parameters of the pulsar are $P_{\rm ms} = 2$ and $B_{12} = 6$.

ered in this paper the value $c(t_{\rm obs} - t)/\lambda$, in Eq. 3, is always less than one. Therefore, a significant part of iron nuclei with energies $\sim 10^{20}$ eV can escape without interaction as postulated by the model of Blasi, Epstein & Olinto (2000). The value of K is estimated from $K = (R_{\rm c}/D_{\rm dif})^3$, where $D_{\rm dif} = (r_{\rm L}ct/3)^{1/2}$ is the diffusion distance of iron nuclei in the magnetic field of the cloud, and $r_{\rm L}$ is the Larmor radius of the iron nuclei with energy E. For the case, $D_{\rm dif} \le R_{\rm c}$, we take $K = 1$. We assume that the giant molecular cloud does not expand. So then the nuclei do not suffer adiabatic energy losses.

2.2 Interaction of nuclei inside the cloud

The part of iron nuclei confined within the molecular cloud, interact with a relatively dense medium suffering desintegrations and pion energy losses. The pions decay into neutrinos and γ-rays. Applying the equilibrium spectrum of iron nuclei (see Eq. 3), we calculate the differential spectra of neutrons (from desintegrations of the iron nuclei), muon neutrinos, and γ-rays (from inelastic collisions of iron). In these calculations we assume that: (1) in a single interaction, the iron nuclei desintegrate into two nuclei and the rest of neutrons is released with the Lorentz factors comparable to the Lorentz factor of the primary nuclei; (2) pions, produced in interactions of iron nuclei with the matter of the cloud, have Lorentz factors comparable to their parent nuclei. They are produced with multiplicities given in Orth & Buffington (1976).

The computations of differential neutron, neutrino, and γ-ray spectra have been done for the pulsar with the surface magnetic field $B_{12} = 6$ (typical of the observed radio pulsars) and the initial period $P_{\rm ms} = 2$. Such a pulsar is able to accelerate nuclei to such high energies (see Eq. 1) that neutrons from their desintegration fulfil the observational constraint put by the excess of cosmic ray particles at $10^{7.9} - 10^{8.5}$ GeV (Hayashida et al. 1999, Bellido et al. 2001). The pulsar born with such parameters slows down

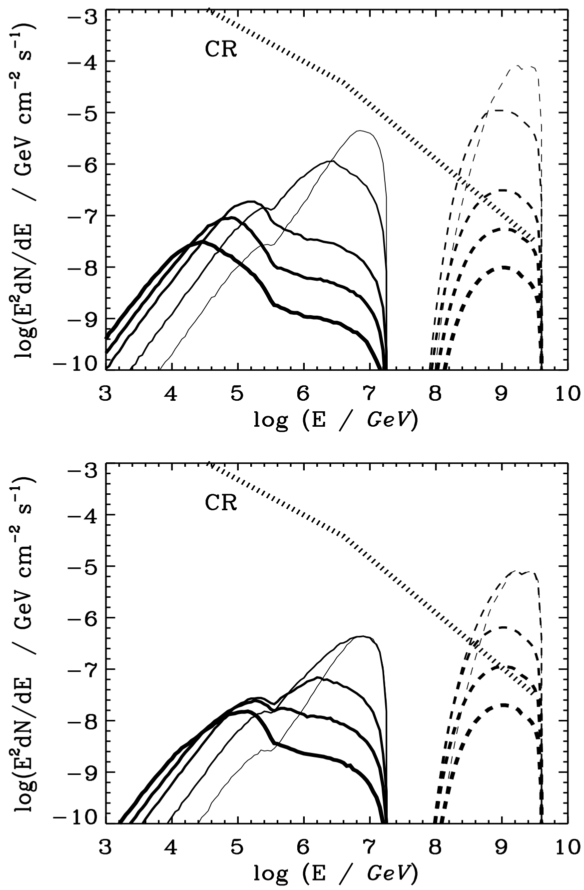

Figure 2. The differential spectra of neutrons (dashed curves) and γ-rays (full curves) observed from the Galactic Center on Earth at the time $10, 10^2, 10^3, 3\times10^3$, and 10^4 yrs (from the thinnest to the thickest curve) after the formation of the pulsar. The initial parameters of the pulsar are as in Fig. 1. The thick dotted curve shows schematically the observed cosmic ray spectrum (see e.g. Boratav & Watson 2000) within the 20° circle.

due to the dipole energy losses to 11 ms after 10^2 yr, 34 ms (10^3 yr), 60 ms (3×10^3 yr), and to 106 ms (10^4 yr). So then it is still fast enough to produce pulsaed γ-rays (Crab and Vela type pulsars).

As an example in Fig. 1 we show the spectra of neutrons (dashed curves) and γ-rays (full curves) produced by the iron nuclei inside a cloud with the radius $R_{\rm c} = 10$ pc, the density $n_{\rm c} = 10^3$ cm^{-3} (the cloud mass $10^5 M_\odot$), and the magnetic field $B_{\rm c} = 10^{-4}$ G at different times after the pulsar formation $t_{\rm obs} = 10, 10^2, 10^3, 3\times10^3$, and 10^4 yrs. As expected, the spectra of neutrons extend up to a few 10^{18} eV. However, their intensities at these highest energies significantly drop with time after the pulsar formation due to the escape of iron nuclei from the cloud for the time $t_{\rm obs} > 10$ yr, which is caused by their diffusion in the magnetic field. Due to the large multiplicities of pion production at these high energies, the maximum energies of neutrinos and γ-rays are about 2 orders of magnitude lower than for neutrons. Their spectra at the higiest energies also drop with time due to the escape of nuclei from the cloud.

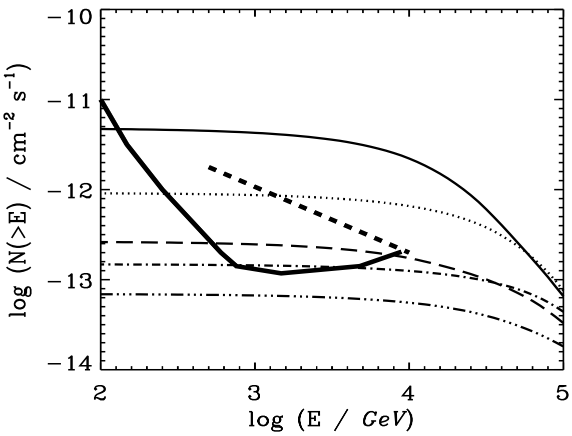

Figure 3. The integral spectra of γ-rays produced in hadronic interactions of iron nuclei with the matter of the molecular cloud at the Galactic Center for the models considered in the text: I (full curve), II (dotted), III (dot-dashed), and IV (dot-dot-dot-dashed), and V (dashed). The thick-dashed and full curves show the sensitivity of the operating HEGRA System and planned CANGAROO III, HESS, and VERITAS systems for a 50-hour exposure to a single source (Lorenz 2001, and references therein).

3 NEUTRONS, NEUTRINOS, AND GAMMA-RAYS ON EARTH

The large distance to the GC, $D_{\rm GC} \approx 8.5$ kpc, has influence on the expected fluxes of neutrons and γ-rays measured on Earth, due to the decay of unstable neutrons and the absorption of γ-rays in the microwave background radiation (MBR). The mean free path for neutrons depends only on their energy, $\lambda_{\rm N} = c\tau_{\rm N}\gamma_{\rm N} \approx 9.8E_{\rm N,EeV}$ kpc, where a neutron's lifetime is $\tau_{\rm N} = 918$ s, its energy $E_{\rm N} = 9.38\times 10^{-10}\gamma_{\rm N}$ in EeV, and $\gamma_{\rm N}$ is the Lorentz factor. The mean free path for the absorption of photons in MBR, $\lambda_{\gamma\gamma}$, was computed in several papers just after the discovery of MBR (e.g. Gould & Schreder 1966). $\lambda_{\gamma\gamma}$ becomes comparable to the distance of the GC at energies of ~ 1 PeV. Therefore the fluxes of neutrons and γ-rays observed on Earth are reduced by the factor $\exp(-D_{\rm GC}/\lambda_{\gamma\gamma;\rm N})$, where $\lambda_{\gamma\gamma;\rm N} = \lambda_{\gamma\gamma}$ or $\lambda_{\rm N}$ respectively. In Fig. 2, we show the fluxes of neutrons and γ-rays observed on Earth at different times after the pulsar formation for the case of the pulsar with the previously mentioned initial parameters and two different sets of parameters describing the medium in the GC region mentioned in section 2: the case of the molecular cloud (the upper figure), and the case of a more extended and lower density region around the GC (the lower figure). The comparison of Figs. 1, and 2 allows us to conclude that the absorption effects of γ-rays become important in the PeV energy range, and that neutrons with energies below $\sim 10^8$ GeV are not able to reach the Earth. Since the propagation of neutrinos is not influenced by any process, their fluxes can be simply obtained for the known distance to the GC. In Fig. 2 we mark also the observed spectrum of cosmic rays (CR) below 3×10^{18} eV within the $20^{\rm o}$ circle (the analysis box of the AGASA data). We find that only the pulsars born within the last $\sim 3\times 10^3$ yrs are able to provide fluxes of neutrons which exceed the CR limit, provided that they accelerate nuclei with the efficiency $\xi = 1$ (see Eq. 2).

Table 1. Gamma-rays and neutrinos from the Galactic Center.

Model	$N_\gamma(>1$ TeV)	$N_\gamma(>10$ TeV)	$N_\nu^{\rm a}$	$N_\nu^{\rm na}$
(I)	4.3×10^{-12}	2.2×10^{-12}	23	30
(II)	8.7×10^{-13}	6.6×10^{-13}	11	16
(III)	1.4×10^{-13}	1.25×10^{-13}	4.2	7.1
(IV)	2.5×10^{-13}	1.7×10^{-13}	5.3	8.8
(V)	6.7×10^{-14}	5.5×10^{-14}	2.0	3.8

4 DISCUSSION AND CONCLUSION

The SUGAR group estimates the flux of particles which causes reported excess of the cosmic ray particles in the energy range $10^{17.9} - 10^{18.5}$ eV on $(9\pm 3)\times 10^{-14}$ m^{-3} s^{-1} (Bellido et al. 2001). If this excess is caused by neutrons produced in the pulsar model discussed here, then the expected flux of neutrons can be compared with the observed one. Basing on this normalization we predict the fluxes of neutrinos and gamma-rays on Earth. This procedure allows us to derive the free parameter of our model (i.e. the efficiency ξ of iron acceleration by the pulsar) and limit the age of the pulsar for other fixed parameters, $P, B, R_{\rm c}, n_{\rm c}, B_{\rm c}$, which are in fact constrained by the observations. We consider five different sets of parameters describing our scenario: model (I) R = 10 pc, $n = 10^3$ cm^{-3}, $B_{\rm c} = 10^{-4}$ G, $t_{\rm obs} = 10^4$ yr; (II) $t_{\rm obs} = 3\times 10^3$ yr and other parameters as above; (III) $t_{\rm obs} = 10^3$ yr and other parameters as above; (IV) R = 50 pc, $n = 10^2$ cm^{-3}, $B_{\rm c} = 3\times 10^{-5}$ G, $t_{\rm obs} = 10^4$ yr; and (V) $t_{\rm obs} = 3\times 10^3$ yr and other parameters as in (IV). They all concern two sets of parameters for the medium in which the pulsar is formed, and differ in the pulsar's age which is not constrained by any observations. In all these models we assume that the pulsar is born with $B = 6\times 10^{12}$ G and $P_{\rm o} = 2$ ms. Normalizing the predicted neutron flux to the observed excess of CR particles we derive the value of the parameter ξ which has to be $\xi \approx 1$ (model I), 0.18 (II), 0.03 (III), 0.3 (IV), and 0.09 (V).

Using the above estimates for ξ we can now predict the expected fluxes of γ-rays and muon neutrinos and antineutrinos in the case of every model. The integral spectra of γ-rays from the GC region are presented in Fig. 3, together with the sensitivities of the present HEGRA telescope system and the planned next generation of telescopes, i.e. CANGAROO III, HESS, VERITAS. We also report in Table 1 the γ-ray fluxes above 1 TeV and 10 TeV in units cm^{-2} s^{-1}. Although the γ-ray spectra have a maximum above 10 TeV for all models, the γ-ray fluxes in the energy range 1-10 TeV produced in models, (I) $\sim 2.1\times 10^{-12}$ cm^{-2} s^{-1}, and (II) $\sim 2.1\times 10^{-13}$ cm^{-2} s^{-1}, and probably also in (IV) $\sim 8\times 10^{-14}$ cm^{-2} s^{-1}, should be observed by the future systems of Cherenkov telescopes of the CANGAROO III, HESS, and VERITAS type. Models (III) and (V) predict fluxes below the sensitivity limit of these Observatories. Only the HEGRA Collaboration observed the Galactic disk including the GC region (Pöhlhofer et al. 1999). The upper limit on the possible sources, equals 1/4 Crab in the Galactic plane which is above the γ-ray flux predicted even by the model (I). However, since the GC region can be observed by

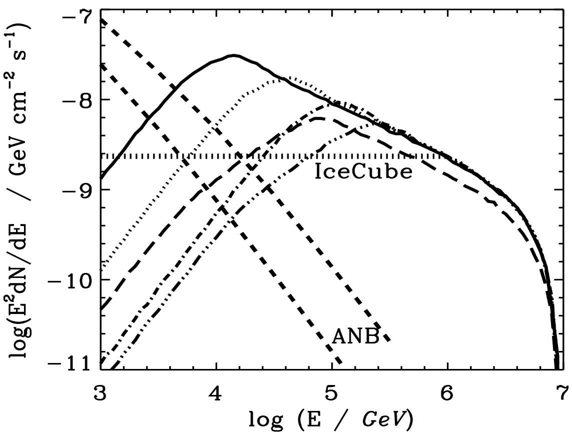

Figure 4. The differential spectra of muon neutrinos and antineutrinos produced in hadronic interactions of iron nuclei with the matter of a molecular cloud at the Galactic Center for the models discussed in Fig. 3. The dashed curves indicate the atmospheric neutrino background, ANB, (Lipari 1993) within a 1^o of the source and the dotted line shows the 3 yr sensitivity of the IceCube detector (Hill 2001).

this experiment only at zenith angles larger than 60^o, this limit does not refer to the GC region.

In Fig. 4 we show the muon neutrino and anti-neutrino spectra expected in the discussed model. At energies > 10 TeV, these spectra are above the expected flux of atmospheric neutrino background (ANB) and also above the 3 yr sensitivity limit of the planned large size neutrino detector IceCube (Hill 2001). We estimate the number of muon neutrino events during one year in the IceCube detector basing on the calculations of the likelihood of detecting such neutrinos by a detector with a surface area of 1 km^2 obtained by Gaisser & Grillo (1987). The results of these calculations are shown in Table 1. We distinguish the case of neutrinos coming to the neutrino detector from directions close to the horizon, i.e. not absorbed by the Earth ($N_\nu^{\rm na}$), and neutrinos which arrive moving upward from the nadir direction, i.e. partially absorbed by the Earth ($N_\nu^{\rm a}$) (for absorption coefficients see Gandhi 2000). From Table 1 it is clear that the IceCube detector should detect a few up to several neutrinos per year from the Galactic Center region provided that the excess of cosmic rays at $\sim 10^{18}$ eV from the GC region is caused by neutrons from desintegrations of iron nuclei, accelerated by a very fast pulsar. The detection of the predicted fluxes of neutrinos from the Galactic Center (or lack) will also place constraints on the recent model of extremely high energy cosmic ray production in the pulsar scenario (Blasi, Epstein & Olinto 2000), since the parent iron nuclei which inject neutrons with energies $\sim 10^{18}$ eV, have to be accelerated to energies $\sim 10^{20}$ eV.

The EGRET detector on board the Compton GRO has detected a strong γ-ray source with luminosity of $\sim 2\times10^{37}$ erg s^{-1} (Mayer-Hasselwander et al. 1998). This emission seems to come from the extended region with the radius of $\sim$ 80 pc around the GC. In another paper (in preparation) we suggest that this emission can be explained in terms of the general scenario discussed here if a part of energy of the accelerated iron nuclei is transferred to the relativistic positrons due to the resonant scattering in the pulsar shock region (see Gallant & Arons 1994). These positrons, accumulated in the cloud, produce high energy radiation in synchrotron and inverse Compton processes.

ACKNOWLEDGEMENTS

This work is supported by the Polish KBN grant No. 5P03D02521.

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